# Testbed Evaluation of Multi-Travel Mode in Virtual Reality


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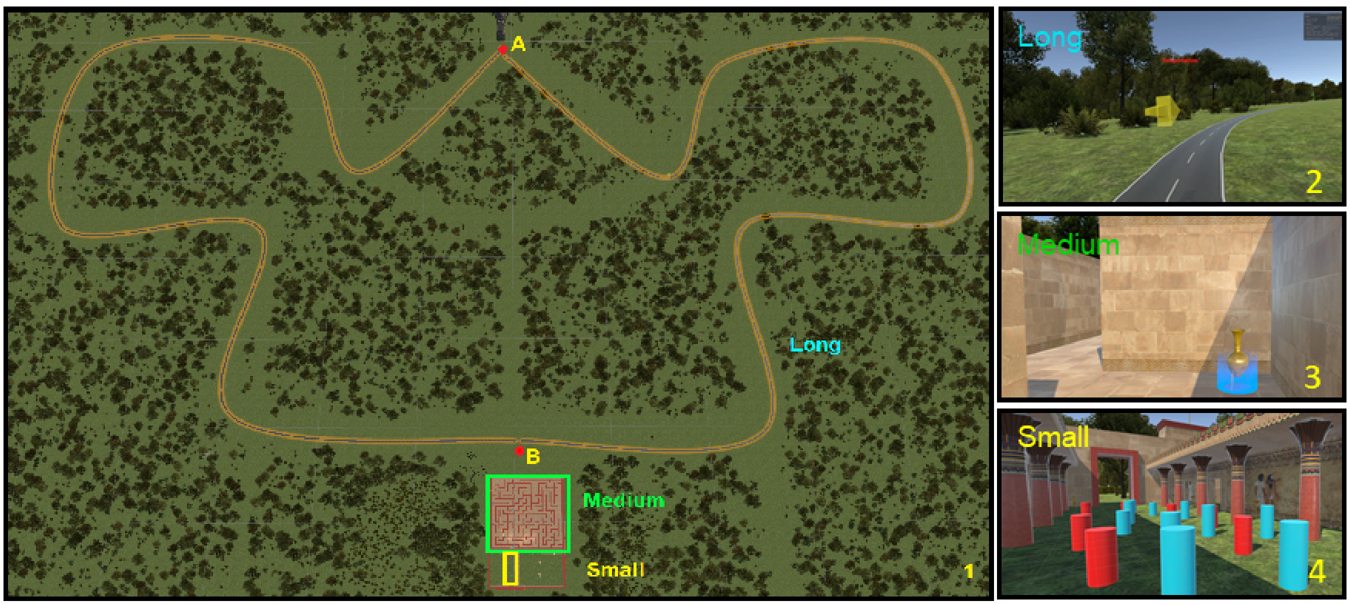



**Figure 1: (1) The Testbed environment LUTE, with large, medium, and small environments. The highlighted orange line represents the two roads from A to B in the large environment requiring (2) long-distance travel along a long narrow road. The green rectangle represents the medium environment requiring (3) medium-distance travel through a maze with target vases to collect. The yellow rectangle represents the small environment, requiring (4) short-distance travel within a small space with red and blue cylindrical objects to collect (blue) or avoid (red).**


## ABSTRACT

Most VR applications, regardless of travel distance or complexity of the Virtual Environment, provide only a single locomotion technique for users. Often, travel might require different levels of precision and speed (travel time and effort). Different locomotion techniques will produce different levels of comfort (cybersickness and fatigue) for various distances. A single locomotion technique does not satisfy all the requirements. In this paper, we introduce a Multi- Travel mode that uses different pre-selected locomotion techniques for different travel distances. The Multi-Travel mode uses Teleportation for long-distance travel, Touch-pad navigation for medium- distance travel and TriggerWalking for small- distance travel. Often, virtual environments are explored standing up, which is one of the contributing factors of physical fatigue since it involves high energy expenditure compared to sitting. To evaluate the Multi-Travel mode and pose (sitting and standing), we used LUTE, a standard testbed environment for long-, medium-, and short- distance travel. We tested the user performance, usability, and comfort of the between-subjects effect of travel technique (Multi- Travel mode, Teleportation or Thumb-pad locomotion in isolation) and within-subject effect of pose (seated/standing). While Multi-Travel mode did not outperform the other two locomotion techniques, We found that participants prefer sitting while using Touch-pad navigation and prefer standing while using Teleportation. Cybersickness was significantly higher while using Touch-pad navigation compared to Teleportation. In addition, the standing pose resulted in higher collection scores compared to sitting.

## CCS CONCEPTS

• **Computing methodologies → Virtual reality**; • **Human-centered computing → *Interaction devices***; *Empirical studies in HCI*; *User centered design*; User studies.

## KEYWORDS

Virtual Reality, Locomotion, Evaluation

## 1 INTRODUCTION

Virtual Reality (VR) technologies have come a long way in terms of the ergonomics of the headsets, resolution, and field-of-view of the displays, quality of the rendering, and richness of spatial sound. Interaction capabilities have improved with multi-function gamepads and tracked hand-held controllers such as those supplied with HTC Vive and Oculus Rift systems. However, the most important interaction, *locomotion* or moving about in the virtual environment (VE), has not yet been solved for the general case. The goal of our work is to take a step toward identifying a general solution to the locomotion problem. In popular video games such as *Grand Theft Auto* and *Assassin's Creed*, much of the appeal comes from the player's ability to explore worlds, buildings, jungles, and galaxies–both realistic and fictional. A VR system with a poor locomotion technique can reduce user enjoyment of virtual experiences and possibly produce cybersickness.

Limited physical space and tracker coverage of that space are major constraints on virtual locomotion techniques. While real walking has been shown to be the most natural and presence-inducing [37], it is not feasible for virtual spaces which are many times larger than, for instance, the effective tracking area of the popular Lighthouse Tracker. Consequently, many locomotion techniques are designed to reduce the physical space required while enabling the exploration of large virtual spaces. Among these are methods where the user moves very little or not at all, e.g., teleportation, flying with a joystick, and methods that map body gestures to steps, e.g., stepping/walking in place or pumping the arms as if running.

The work reported here was motivated by the observation that in the real world people use different modes of transportation and locomotion when they are traveling different distances and performing different tasks: We use motor vehicles for long and medium distances, e.g., trips across the country for recreation or across town for shopping, and we walk for medium and short distances, e.g., when picking flowers or working in a building. People choose a method of travel that meets their preferences and task requirements. The question we address here is whether it will improve VR experiences to have multiple locomotion techniques available in the application and enabling the user to choose which one to use in a specific situation. We also study if switching between locomotion techniques for various travel distances lead to high mental fatigue.

This paper presents a new virtual locomotion system *Multi-Travel mode (M-Travel)* that includes three locomotion options chosen based on their appropriateness for traveling long, medium, or short distances. We include Teleportation (Tele) for traveling long distances [9], Thumb-pad locomotion (TPad) (similar to Joystick flying) for medium distances, and Trigger Walking [28] for short distances.

In this study, the independent variables were Locomotion techniques (Between-subjects variable) and pose (Within-subjects variables). All participants were divided into three between-subject groups based on the travel technique, each of which used one of three techniques: the Multi-Travel mode (M-Travel), the Thumb-pad interface (TPad), or the Teleportation (Tele) interface. We haven't compared M-Travel with Trigger Walking in this experiment since Trigger Walking is only suitable for medium- to small- distance tasks [29]. Each group performed the three tasks, both seated and standing (within-subjects variable). We compared performance (task completion time, collection score and precision), simulator sickness, and workload.

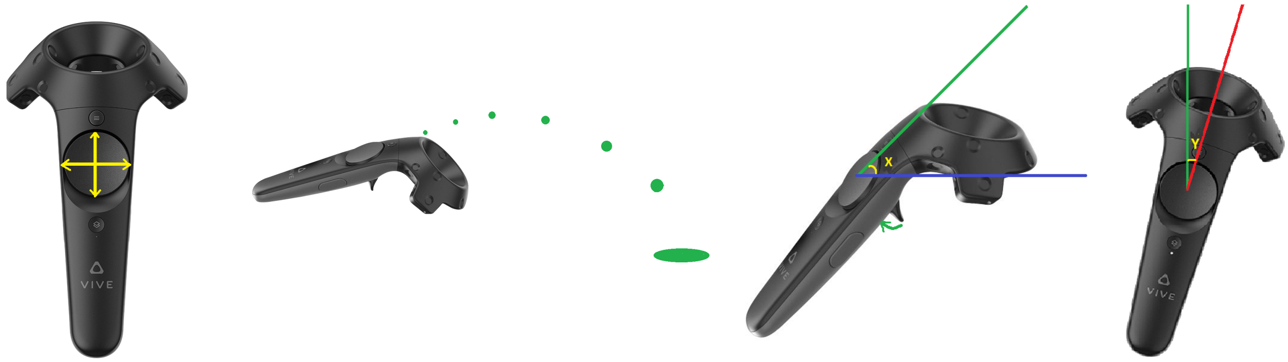
## 2 BACKGROUND

In addition to comparing our Multi-Travel mode to Thumb-pad and Teleportation systems, another goal of our work was to enable comparison of our Thumb-pad and Teleportation results to results of earlier work evaluating those interfaces. To that end, we selected those locomotion techniques from among the many previously described in the literature and for which performance and usability data are available. For the same reasons, we chose tasks and dependent variable measures that are common in virtual locomotion studies.

To bring order to the discussion of the growing number and variety of virtual locomotion techniques, taxonomies have been proposed. Among them are Bowman et al. [7], LaValle and Steven [20], Arns and Lynn [3], and the recent work by Boletsi [5]. Boletsi's literature review is a notable resource; it is a review of the virtual locomotion literature from 2014-2017, identifying 11 types of locomotion interfaces. For each of the 36 papers examined, Boletsi records interaction type, VR motion type, VR interaction space, VR locomotion technique, and the type of empirical study performed.

An ideal, single locomotion technique suitable for all virtual environments and tasks that is deployable on any hardware would be difficult to achieve. Most locomotion interfaces have both advantages and disadvantages. Real walking is the most natural and immersive way to move about in a VR; however, it is limited to the covered tracking space and may require significant levels of exertion. Techniques which use natural walking *gestures*, e.g., walking in place [32], arm swinging [24], and running in place [40], stimulate the vestibular system from their required physical motion, and so help minimize cybersickness. However, these gestural interfaces have issues such as undesirable positional drift (away from the user's starting position in the tracking area) and fatigue. Magical metaphors such as Point Teleport [9], Magic portals [34], and Silver surfer [38] are easy to use and avoid the discomfort of cybersickness and/or fatigue, but they can, due to sudden viewpoint changes, lead to spatial disorientation. Joystick driven movement is common locomotion interface; it is, however, well known for inducing cybersickness [21].

We chose locomotion techniques, we believe are well suited for long-, medium-, and short-distance travel. We eliminated from consideration any technique that regularly causes cybersickness in users, e.g., joystick flying, and for long travel, any technique that induces fatigue when used over time, e.g., natural walking and walking-in-place. For short travel distances, the technique




Thumb-pad Locomotion Teleportation Trigger Walking

**Figure 2: Locomotion Methods**

had to offer easy speed and direction control for close-quarters maneuvering. An additional requirement was that users not be required to change their interaction device should they choose to change the locomotion technique during a virtual experience.

After considering all of the requirements, we chose Point and Teleport [9] for long-distance travel, Thumb-pad locomotion [19] for medium-distance travel, and TriggerWalking [29] for short travel distances. Thumb-pad locomotion and Teleport needs a single hand-held controller, and the TriggerWalking needs two hand-held controllers.

In several user studies that evaluated locomotion techniques in Virtual reality [25, 26, 29, 30, 35, 39], users were standing while performing the tasks. According to Ainsworth et al. [1], the metabolic equivalent (MET) score of standing is 1.8 - 4 compared to sitting 1 - 2.5. This indicates that energy expenditure while standing is more than sitting. Noah et al. [12] studied the performance of joystick navigation while sitting and standing and found no difference in the performance. Terziman et al. [36] evaluated Walking in Place while sitting and standing and found that realism is high while sitting than standing. However, Carello et al. [11] found that users overestimate target distance while standing and underestimate target distance while sitting. Sitting is a natural (Computer games, eating, driving, in front of a computer, driving in a car etc.) pose that is more comfortable than standing. In addition to evaluating the locomotion techniques for different tasks, we also evaluated the locomotion techniques for the different pose (standing and sitting).

We used a formal testbed LUTE (Locomotion usability testing Environment) [31] to evaluate comfort, usability, and performance of the Multi-Travel mode, Touch-pad navigation, and Teleportation. According to Bowman et al. [8], using formal testbeds in evaluating interaction techniques not only leads to a greater understanding of the techniques but also helps in developing robust and better techniques using the knowledge gained through evaluation. Lampton et al. [18] used a Virtual Performance Assessment Battery (VEPAB) to evaluate interaction techniques, including locomotion techniques. Bowman et al. [6] used a testbed evaluation framework (an open medium environment with obstacles) to evaluate the performance of different locomotion techniques in search tasks. Nabiyouni and Bowman [25] used a formal testbed (a hallway with turns) to evaluate hyper-natural transfer function of locomotion techniques. We used LUTE [31] since it allows us to evaluate the locomotion techniques for different environment sizes and complexity.

The requirements for the task in our study were that

(1) the task must be easy to learn, and,
(2) the user must move around in the VE,
(3) must interact with objects in the environment,
(4) task performance must be easily measured,
(5) ideally, the task should be easy to implement.

In addition, we desired tasks that had been used in VR evaluation studies previously. We chose the following tasks which met these criteria:

(1) travel along a road or path with good clearance and good visibility, e.g., [17]. Specifically, our long-distance task was to simply follow course indicators along a road with minimal obscuring vegetation and objects.
(2) explore space and find and collect objects, e.g., [27], and
(3) maneuver through a crowded space and avoid colliding with objects in the space, e.g., [19].

The medium- distance task was finding and collecting objects in a maze. The short- distance task was maneuvering in a cluttered environment, touching some objects and avoiding touching others. The environments and tasks are described more fully in sections 4.2 and 4.3.

## 2.1 Locomotion Methods

Our rationale for the locomotion techniques for Multi-Travel mode is that [9] reported Teleportation as comfortable and efficient for traveling in the presence of few obstacles, and so we chose this technique for the long-distance task. Thumb-pad walking with tunneling effects [13] and the slower speed is used for the medium-distance task since it is easy to use and learn. If there is poor visibility due to walls and turns [9], Teleportation does not work properly, but Trigger Walking has been shown to be efficient and realistic for small-space navigation [29], so it was chosen for the short-distance task.

This section explains the locomotion techniques used in our experimental setup. We used the HTC Vive hand-held controllers for Thumb-pad locomotion, Teleportation, and TriggerWalking.

## 2.2 Vive Thumb-pad Locomotion

Thumb-pad locomotion (similar to a joystick condition [19]) enabled the user to move in the environment by touching the Thumb-pad in the direction of the desired movement as shown in Figure 2, similar to joystick navigation controls. The further the thumb was from the centre of the Thumb-pad, the faster the user moves. The maximum speed was set to 1 m/s, similar to Kitson et al. [17] for the medium-distance task condition and to 2 m/s for the long-distance task condition. We chose to use Thumb-pad locomotion instead of a joystick to avoid having to switch devices between experimental trials, which might have caused breaks in presence. To avoid discomfort due to cybersickness, we included a tunnelling effect, whereby faster movement made the field of view shrink and vice versa, which has been shown to reduce the effects of cybersickness [13].

## 2.3 Teleportation

In this technique, when the Thumb-pad was pressed, a parabola was projected out of the controller and onto the ground, indicating the destination point. When the Thumb-pad was released, the viewpoint of the participant changed to the target destination. An increase in the angle of elevation of the controller increased the range of the parabola and thus the distance to travel. The projection on the ground was green for the areas for which navigation was allowed (e.g., roads, grass), and turned red if the target location was placed on areas where navigation was not allowed (e.g., walls, objects, trees).

## 2.4 Trigger Walking

TriggerWalking (TW) used two HTC Vive hand-held controllers to mimic the mechanics of human bipedal walking in VR. Each hand controller is analogous to a leg, and each trigger pull moved the user one step. The direction of the movement was the average of the yaw (rotation about the up-axis) direction of the controllers, and unlike gaze-directed locomotion techniques, giving the user the ability to move in one direction and look in another. In human walking, a human can either increase the frequency of stepping or take longer strides to move faster. A similar concept was used to manipulate the speed of movement in TriggerWalking. The speed of movement could be increased by increasing the frequency of trigger pulls, or by increasing the tilt angle (angle to the ground plane) of the controller. The maximum angle to which the velocity was scaled was $90^o$, and if the angle was greater than $90^o$, the maximum speed was clamped to 2 m/s. The increase in speed was linear and proportional to the elevation angle. The average speed used in TriggerWalking was 0.70 m/s [29].

# 3 SYSTEM OVERVIEW

## 3.1 Equipment

The evaluation of M-Travel took place in a 7m×5m laboratory room space. Participants wore an HTC Vive HMD with a resolution of 1080×1200 per eye, a field-of-view of 110° and a frame rate of 90Hz. Lighthouse trackers were used to tracking the headset and controllers. We used a computer with an Intel Core i7-6700 processor, 16GB of main memory, and an NVIDIA GeForce GTX 1080 graphics card.

**Table 1: Direction and Speed control of M-Travel, Tpad and Tele**

| Tech | Direction Control | Speed Control |
|---|---|---|
| **T-pad** | Direction of Thumb from the center of T-pad | Displacement from center of T-pad capped at 2 m/s |
| **Tele** | Yaw of the controller | Instantaneous with infinite speed |
| **TW** | Average of yaw of the controllers | Tilt angle capped at 2 m/s |

## 3.2 Virtual Environment

*3.2.1* ***Software***. The Unity3D engine version 2017.4.3 was used to render the virtual environment. GAIA[1] was used to generate a large environment, and the medium and small environment 3D assets were imported from the Unity asset store. We used LUTE (Locomotion Usability Test Environment) as the software framework for the experiment discussed in the previous chapter.

*3.2.2* ***Virtual Environment***. The experiment environment consisted of a large environment of size 2000m×2000m, similar to [31]. Figure 1 (1) shows the screen-shot of half of the environment we have used in the experiment. In the middle of the environment, there was a tall tower (Point A) to give participants a landmark. For the long-distance task, we generated two 1m wide roads with six bends and a length of 1,500m from point A to B, as indicated by the orange in Figure 1. Only one road is displayed, and the roads were switched to mitigate the effect of the direction the user initially navigates. The environment included vegetation (grass, shrubs, bushes, and trees), as shown in Figure 1 (2). For the medium-distance task, a maze was set up with a 300m long and 3m wide path. The walls had a stone texture, and the maze had a number of bends and dead ends, as shown in Figure 1 (3). A total of 20 highlighted vases were placed throughout the maze. At the end of the maze, there was a 20m×10m area that included 20 blue and 20 red cylinders positioned between 0.7m and a minimum of 0.4m apart (Figure 1 (4)). The short-distance task used this space with pillars and objects in addition to the cylinders.

# 4 STUDY DESIGN

## 4.1 Design

To evaluate the performance, usability, and comfort of Multi-Travel mode, Thumb-pad locomotion, and Teleportation, we conducted a 3×2 mixed-factorial experiment with two independent variables *Locomotion Technique* (M-Travel, Thumb-pad, Teleportation) and *pose* (Sitting, Standing). The experimental design was approved by the Human Ethics Committee of the University of Canterbury. Each

[1] http://www.procedural-worlds.com/gaia/

participant was randomly assigned to one of the following three between-subjects conditions:

(1) **Multi-Travel mode (M-Travel)**: The participants were assigned a locomotion technique depending on the tasks, i.e., Teleportation for long distances, Thumb-pad for medium distances, and Trigger Walking for short distances.
(2) **Thumb-pad (TPad)**: The participants were allowed to use only Thumb-pad during all tasks.
(3) **Teleportation (Tele)**: The participants were allowed to use the only Teleportation during all tasks.

Each participant had to complete the tasks both sitting and standing. We used a counter-balanced Latin Square on the pose in order to avoid ordering effects.

(1) **Sitting**: The participants performed the task with one of the locomotion techniques while sitting on a rotating and tiltable chair. No data from the chair was used in the locomotion interfaces for either direction or speed.
(2) **Standing**: The participants performed the task with one of the locomotion techniques while standing in place.

*4.1.1* ***Hypotheses***. Building upon the previously reported results in the relevant literature, our hypotheses were:

(1) Using M-Travel mode for large, medium, and short distances will be more comfortable compared to using a single locomotion technique only (TPad or Tele).
(2) Using M-Travel mode for large, medium, and short distances will be perceived as more usable compared to using a single locomotion technique only (TPad or Tele)
(3) Using M-Travel mode for large, medium, and short distances will be more efficient (lower task-completion time and more objects collected) than using a single locomotion technique (TPad or Tele).
(4) Sitting will be more comfortable (lower SSQ [16] and NASA-TLX [14] scores) compared to Standing for all conditions.

## 4.2 Measures

To measure subjective feelings of Comfort and Usability, we adopted previously validated questionnaires.

*4.2.1* ***Comfort***. We consider comfort as *"lack of unease and pain"*. Cybersickness was measured using the standard Simulator Sickness Questionnaire (SSQ) [15]. There were four values to choose from 0–3 for each question. The questionnaire was administered before the experiment and after each within-subjects condition. To measure physical and mental fatigue (workload), we used the NASA-TLX [14] in this experiment. The questionnaire was administered after each within-subjects condition.

*4.2.2* ***Usability***. The usability of the Multi-Travel mode was compared to TPad and Tele locomotion techniques using System Usability Scale (SUS) [10]. The questionnaire was administered after each within-subjects conditions.

*4.2.3* ***Performance***. The system automatically logged the individual time taken to complete long-, medium-, and short-distance tasks, number of vases collected in the medium-distance task, number of blue and red cylinders collected in medium- and short-distance task. In addition, it also logged the number of collisions with the walls and objects in the middle- and short-distance tasks.

## 4.3 Participants

A total of 45 participants (male = 23, female = 22 , other = 0, and ages 18—45 (*M*=26.85, *SD*=5.69)) participated in the experiment. We recruited participants from the local university using on-campus fliers and posts on social network platforms. We ensured that all participants had a normal or corrected-to-normal vision. Twenty-one participants wore glasses during the experiment, and four wore contact lenses. Seventeen participants had no prior experience with 3D computer games. The height of the participants varied from 1.35—1.89m (*M*=1.68, *SD*=10.1). The total time taken for explanation, practice, task completion, filling in the questionnaires and debriefing was about 40 minutes per subject. Participants were allowed to take breaks at any time between the conditions or during the experiment if they felt uncomfortable or needed a rest.

## 4.4 Experiment Procedure

*4.4.1* ***Pre-Experiment***. Participants were given an information sheet outlining the experiment, which was also explained by the experimenter. Participants had to sign the consent form before filling in the demographic questionnaire. Before starting the first condition, the participant was asked to fill in an SSQ simulator sickness questionnaire to indicate a discomfort score, which acted as a baseline. Before commencing the actual tasks, the participant was informed that they could stop the experiment at any point if they felt uncomfortable or sick.

*4.4.2* ***Procedure***. Depending on which locomotion technique the participant was assigned to (M-Travel, TPad or Tele), a practice session helped instruct the participant how to move around a simple environment until they were comfortable using the locomotion technique. A message was displayed explaining the first task, and the participant pulled the trigger to start the task. For the first task, the participant had to move along a narrow road, following a guiding arrow, as shown in Figure 4, in order to reach six checkpoints indicated by green cylindrical highlighted areas. After reaching the final checkpoint, the participant was directed to enter a medium-size semi-indoor maze with turns.

A message was displayed instructing user to collect as many vases as possible, and the collection score was displayed in the HMD. Twenty highlighted vases (treasures) were placed in the maze as shown in Figure. 3, inset. The participant had to carefully look around to locate them, and then reach out to "touch" them with the controller to collect them. Participants were warned prior to the study to avoid bumping into walls, and the view in the headset faded to remind them whenever they hit a wall. The arrow guided them through the maze, and participants were given three minutes to complete the task. After collecting as many vases as possible within the limited time, they were teleported to the end of the maze.

At the end of the maze, the participant was instructed to perform the short-distance task which was to move through blue cylinders to collect them, and avoid red cylinders as shown in Figure. 1 (4). The collection score was displayed to the participant, and they had

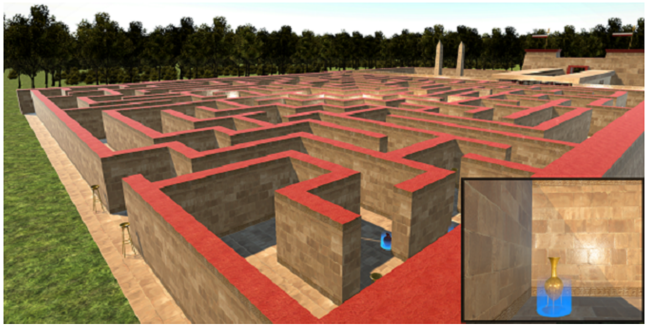


**Figure 3: Medium Environment (Maze with target vase to collect)**

to reach all 12 blue cylinders within one minute. Once done, a message was displayed to take off the headset, and the participant was instructed to complete SSQ, SUS, and NASA-TLX questionnaires on computer. When the questionnaire was completed, the user then repeated the second pose condition using the same locomotion technique, and was asked to fill in the same questionnaires again.

*4.4.3* ***Post-Experiment.*** At the end of the whole experiment, we administered a post-experiment questionnaire about preference, the reasons for their preferences, and any comments they wanted to provide.

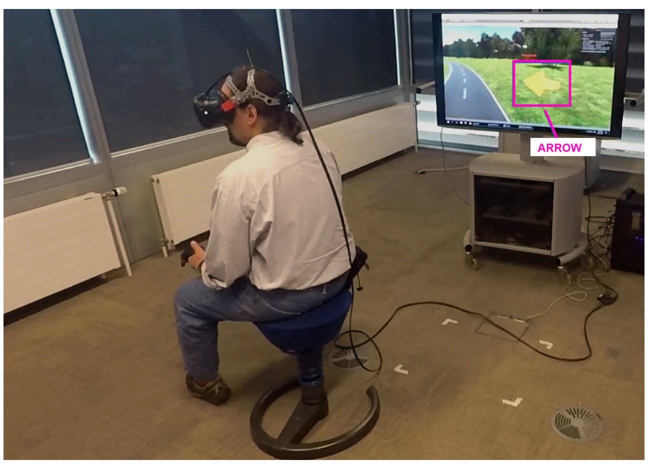



**Figure 4: Seated user with arrow guiding through the long-distance task**

# 5 RESULTS

## 5.1 Statistical Analysis

The data were analyzed with SPSS using a mixed ANOVA. The statistical significance level was set to $\alpha = 0.05$. Normal distribution of the data was assessed with a Shapiro-Wilk test. When the data were non-normal, an Aligned Rank Transformation was applied. When a pair-wise comparison was carried out, Bonferroni correction was applied to counteract inflated Type I errors due to multiple comparisons. Two participants, one in the TPad and one in the M-Travel conditions, experienced nausea and did not complete the study. Their data were not included in the statistical analysis.

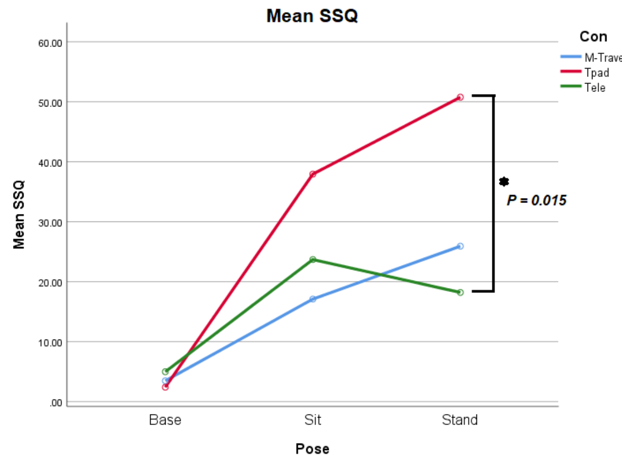



**Figure 5: Mean SSQ scores (Base, Sitting and Standing)**

## 5.2 Comfort

*5.2.1* ***Cybersickness.*** Figure 5 shows the mean SSQ scores by condition. We compared baseline(pre-experiment), sitting, and standing SSQ scores. There was a significant main effect of pose on the total SSQ score, $F(2,80)=3.482$, $p=0.035$. There was also a significant main effect of locomotion technique on SSQ scores $F(2,40)=3.68$, $p=0.034$. Post-hoc tests showed that there was a significant difference in SSQ scores between TPad and Tele ($p=0.015$).

*5.2.2* ***Work Load.*** NASA Task Load Index (NASA-TLX) was used to compare the Physical, Mental, and Temporal demands of tasks for different pose and locomotion techniques. Table 2 lists the mean and standard deviation values of NASA-TLX question scores of M-Travel, TPad, and Tele conditions for different poses. The questions in the NASA-TLX indicated Mental Demand, Physical Demand, Temporal Demand, Effort, Performance, and Frustration, respectively. They were no significant main effects of pose on Nasa-TLX. There were no significant main effects of pose on Mental Demand ($F(1,40)=3.104$, $p=0.086$), Physical Demand ($F(1,40)=1.379$, $p=0.264$), Temporal Demand ($F(1,40)=1.515$, $p=0.232$), Effort ($F(1,40)=2.515$, $p=0.094$), Performance ($F(1,40)=0.317$, $p=0.730$) or Frustration ($F(1,40)=1.189$, $p=0.315$) for the tasks. There were no significant main effects of locomotion technique on Mental Demand ($F(2,40)=0.10$, $p=0.99$), Physical Demand ($F(2,40)=1.793$, $p=0.18$), Temporal Demand ($F(2,40)=0.807$, $p=0.453$), Effort ($F(2,40)=0.478$, $p=0.624$), Performance ($F(2,40)=0.234$, $p=0.793$) or Frustration ($F(2,40)=0.317$, $p=0.730$) for the tasks.

## 5.3 Usability

There were no main effects for pose on the SUS $F(1,40)=0.087$, $p=0.769$, for locomotion techniques $F(2,40)=1.331$, $p=0.276$.‘

**Table 2: Mean NASA-TLX scores**

| TLX | M-Travel | | Tpad | | Tele | |
|---|---|---|---|---|---|---|
| | Sit | Stand | Sit | Stand | Sit | Stand |
| Mental Demand (M) | 57.6 | 51.9 | 63.4 | 48.9 | 54.5 | 54.3 |
| SD | 19.50 | 26.29 | 20.82 | 28.36 | 33.78 | 27.69 |
| Physical Demand (M) | 24.4 | 24 | 25.2 | 25.8 | 32.7 | 43.1 |
| SD | 24.39 | 18.92 | 17.46 | 22.09 | 28.53 | 28.14 |
| Temporal Demand (M) | 37.8 | 44.4 | 42.4 | 36.1 | 48 | 51.9 |
| SD | 26.47 | 24.59 | 26.91 | 23.94 | 31.73 | 23.75 |
| Effort (M ) | 71.4 | 81.1 | 69.5 | 76.3 | 72.1 | 67.6 |
| SD | 13.01 | 12.27 | 23.63 | 15.46 | 23.54 | 25.58 |
| Performance (M) | 50.8 | 46.9 | 54.2 | 54.6 | 53.3 | 55.5 |
| SD | 22.72 | 26.90 | 26.39 | 30.90 | 31.25 | 23.83 |
| Frustration (M) | 32 | 31.6 | 30.3 | 25.6 | 33.7 | 37.5 |
| SD | 24.27 | 28.34 | 26.05 | 25.52 | 26.98 | 29.20 |

**Table 3: Mean SUS scores**

| SUS | M-Travel | | Tpad | | Tele | |
|---|---|---|---|---|---|---|
| | Sit | Stand | Sit | Stand | Sit | Stand |
| M | 80.18 | 79.46 | 69.47 | 73.21 | 76.50 | 74.83 |
| SD | 12.77 | 17.84 | 16.24 | 14.80 | 11.29 | 16.20 |

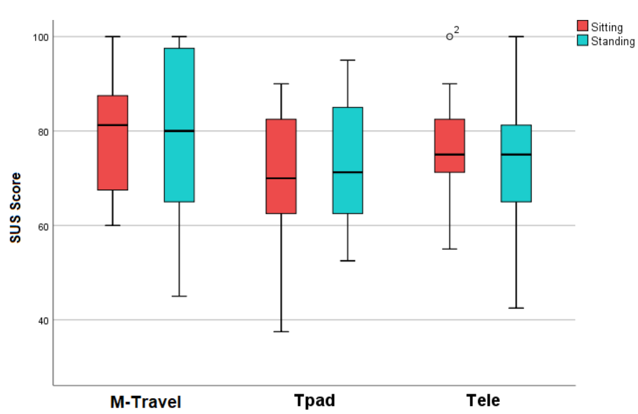



**Figure 6: SUS Box plots. The whiskers represent max and min SUS scores**

## 5.4 Performance

The mean and standard deviation values of Task Completion Time, Collection Score and Collisions are summarized in Table 4.

*5.4.1* ***Task completion time.*** There were no significant differences between the task completion times for the locomotion techniques for Long ($F(2,40)=0.214$, $p=0.813$ ), Medium ($F(2,40)=1.098$, $p=0.385$), and Short ($F(2,40)=0.305$, $p=0.746$) tasks. No significant differences were identified between task completion time for Long ($F(2,40)=2.161$, $p=0.186$), Medium ($F(2,40)=0.062$, $p=0.94$), and Short ($F(2,40)=0.081$, $p=0.923$) tasks in either Sitting or Standing conditions.

*5.4.2* *Collection Score.* Since the Long-distance task did not involve collecting objects; there are no collection scores for it. The statistical analysis indicated no significant differences between the collection scores on the Short-distance task for different locomotion techniques ($F(2,40)=0.008$, $p=0.99$). There was a significant difference between the collection scores of the Short-distance task between Sitting and Standing ($F(1,40)=8.78$, $p=0.21$) when we did not consider the locomotion technique as a factor.

*5.4.3* *Collisions.* Mean wall collisions are reported in Table 4. There were no significant effects of locomotion technique ($F(2,40)=0.99$, $p=0.42$) or pose ($F(1,40)=0.06$, $p=0.8$) on wall collisions. There were no significant interaction effects for wall collisions between locomotion technique and pose ($F(2,40)=0.57$, $p=0.58$).

## 5.5 Preference

To find the subjective preference of the participants for pose, we asked the participants to indicate their preferred pose between the sitting and standing. Out of 14 participants who were assigned to the TPad condition to complete the tasks, 78.57% (11) preferred sitting, and 21.42 % (3) preferred standing. Out of 15 participants who were assigned to the Tele condition, 33.33 % (5) preferred sitting, and 66.66%(10) preferred standing. Out of 14 participants who were assigned to the M-Travel condition, 42.85% (6) preferred sitting, and 57.14% (8) preferred standing. The chi-square goodness-of-fit test indicated that the participants preferred sitting in the TPad condition significantly ($\chi^2=4.571$, $p=0.033$).

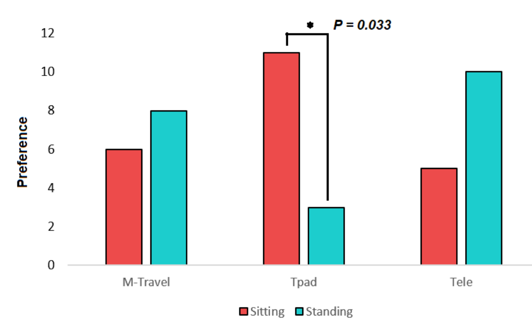



**Figure 7: Preference**

In addition to preference, we asked participants for the reasons behind their preference and obtained some feedback as shown in Table 5. Most of the participants who preferred standing reported that standing made them feel more immersed compared to sitting.

**Table 4: Mean task completion times (seconds), collection scores S, and collisions C**

| Loco | #$T$ Long (s) | | #$T$ Medium (s) | | #$T$ Short (s) | | #$S$ Medium | | #$S$ Short | | #$C$ Wall | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Sit | Stand | Sit | Stand | Sit | Stand | Sit | Stand | Sit | Stand | Sit | Stand |
| M-Travel (M) | 147.1 | 155.4 | 180 | 180 | 60 | 60 | 16 | 14.6 | 16 | 13 | 2.5 | 5 |
| SD | 12.09 | 25.21 | 0 | 0 | 0 | 0 | 4.58 | 0.58 | 4.58 | 4.5 | 0.7 | 1.42 |
| Tpad (M) | 151.50 | 172.7 | 171.7 | 180 | 53.7 | 60 | 19 | 11.5 | 17 | 13.5 | 18.5 | 9 |
| SD | 29.63 | 27.24 | 9.5 | 0 | 7.18 | 0 | 1.86 | 3.6 | 3.25 | 7.09 | 23.3 | 7 |
| Tele (M) | 123.5 | 119.7 | 180 | 167.8 | 55.9 | 55.4 | 13.6 | 14 | 15.6 | 16.3 | 24.2 | 32.8 |
| SD | 40.99 | 41.06 | 0 | 11.39 | 7.06 | 7.82 | 6.51 | 4.58 | 5.86 | 6.35 | 22.35 | 45.69 |

**Table 5: Participant Comments**

| Loco | Pose | Preference |
|---|---|---|
| **M-Travel** | Sitting | Feels more secure and easy<br>Sitting gave extra stability and comfort |
| | Standing | Sitting increased nausea<br>I can control the body well while standing |
| **Tpad** | Sitting | Easier to rotate the body<br>More comfortable<br>Don't have to be worried about balance |
| | Standing | Comfortable to move around the environment<br>Felt more focused on my way and destination<br>It's not real to sit and walk in the scenario |
| **Tele** | Sitting | Felt less balanced especially in the maze<br>Easy to rotate around and comfortable<br>Don't have to worry about tripping over the headset chord |
| | Standing | Standing is easier to change directions<br>Feels harder to move in VE while sitting<br>Standing condition felt more real although I did better in sitting condition |

Looking at the preferences of the participants, they favour Sitting in the TPad condition. A majority of participants indicated that standing made them uncomfortable during the TPad condition. One participant commented that he felt nauseous using Teleportation while sitting. For the Tele condition, a majority of participants indicated that they preferred standing since it gave them more flexibility to move around the virtual environment.

## 6 DISCUSSION

The discussion that follows is organized first around four hypotheses laid out in Section **??**. *Hypothesis 1* states that *Using M-Travel mode for large, medium, and short distances will be more comfortable compared to using a single locomotion technique only (TPad or Tele).* Statistical analysis shows that the Tpad condition induces more cybersickness than Tele. This supports the findings from previous studies [19, 28**?** ]. There was no difference in perceived workload measured using NASA-TLX. Results did not show that M-Travel mode has less perceived cybersickness or work load than Tpad and Tele and hence *Hypothesis 1* was not confirmed.

*Hypothesis 2* states that *Using M-Travel mode (M-Travel) for large, medium, and short distances will be perceived as more usable compared to using a single locomotion technique only (TPad or Tele).* The SUS results of the M-Travel mode were not statistically different from the other locomotion techniques (TPad and Tele). Hence *Hypothesis 2* was not confirmed. However, using the SUS score scale proposed by Bangor et al. [4], the usability of M-Travel (Sit: 80.18, Stand: 79.46), and Tele (Sit: 76.50, Stand: 74.83) is between Good-Excellent and Tpad (Sit: 69.47, Stand: 73.21) is between Ok-Good.

*Hypothesis 3* states that *Using M-Travel mode for large, medium, and short distances will be more efficient (lower task-completion time and more objects collected) than using a single locomotion technique (TPad or Tele).* Participant collection scores were higher while standing compared to sitting, and there were no significant differences in collection scores for different locomotion techniques. One reason the collection scores were different could be because of the differences in eye height while sitting and standing. According to Leyrer et al. [22, 23] standing for locomotion is more natural, and the eye height affects the distance estimation in VR. A reason for not getting a significant difference could be the time constraint in the various tasks (the score of the participants had a ceiling effect). Participant performance showed that there were no significant differences in the task completion times and collisions for pose or locomotion technique. Hence *Hypothesis 3* was not confirmed.

*Hypothesis 4* states that *Sitting is comfortable (less cybersickness and less fatigue) than standing in VE exploration tasks.* Participants standing reported more cybersickness scores compared to the sitting. This might be due to the less frequent body and head movement while sitting, which in turn reduces cybersickness as already reported in a study by Arcioni et al. [2]. Hence *Hypothesis 4* was confirmed. Participant preference confirms that participants preferred sitting compared to standing in the TPad condition. This could be because of minimal head and body movement in sitting than standing [2]. It is interesting to see that in Tele condition, people preferred standing. Previous literature has stated that Teleportation performance is low when there are low visibility [9]. Also, the eye height affects the perception of spatial layout in Virtual Environments [23] and this might be the contributing factor for participants preference.

### 6.1 Limitations

The M-Travel mode implemented for this experiment does not allow participants to switch to a locomotion technique they prefer. The locomotion techniques were chosen for each task based on reports in the literature of their performances in tasks similar to those we implemented in this experiment. Though the participants had a short training session before starting the experiment, there were no measures used to check their proficiency in using the three locomotion techniques. Ruddle et al. [**?** ] found that there is a direct correlation between training the participants to proficiency and their performance in using locomotion techniques to complete a set of tasks. Hence, it is hard to predict their rational preference in choosing a better technique. For example, some techniques might be easy to learn, but not comfortable to use, and some techniques might need some initial training and might be more suitable and comfortable for the task. We did not train the participants long enough to check their proficiency in this case. Time constraints add cognitive load while completing a task and is used in many tasks in games [33]. In our trials before the actual study with our colleagues, they could complete the medium- and short- distance tasks before the allocated times. However, in the experiment, some participants could not finish the medium-distance task in the allocated time.

## 7 CONCLUSION

We introduced M-Travel mode that uses different locomotion techniques based on locomotion tasks. We compared it with Teleportation (Tele) and Thumb-pad (TPad) locomotion to evaluate the comfort and performance of the method. We designed a study to include tasks which required long-, medium-, and short-distance travel. We found that TPad induced more cybersickness than Tele, which supports previous findings in the literature [12, 19, 28]. Based on participant preferences and the SSQ scores, we found that sitting is more comfortable when using TPad locomotion than standing. Secondly, the system did not allow participants to choose between locomotion techniques to complete a task. We speculate that if the participants could switch or choose a locomotion technique according to their preference in a given scenario and task, this may influence their performance. An ideal solution to the current issues in locomotion is to develop a comprehensive locomotion system which gives the user the ability to choose a comfortable and efficient way of navigating through a virtual environment depending on the task, pose, personal preference, size of tracked space, and size of the virtual environment.

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